Progress Report: Full Particle Simulations of Magnetic Reconnection at the Magnetopause

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I. Research Progress During Reporting Period

 In this section we briefly describe our new findings, the progress of our graduate student, and our plans to secure additional sources of funding for this project. The main thrust of this research is to develop an understanding of the collisionless reconnection at the magnetopause. The reconnection literature is littered with papers with erroneous results. This stems from the fact that the particle orbits are quite complex in a current sheet geometry and this makes the traditional linear theory calculations very difficult. The full particle simulations of reconnection *onset* are also equally challenging as (i) collisionless tearing mode tends to have small growth rates unless one goes to very thin layers, (ii) the simulations require high resolution to properly address the saturation of the mode, and (iii) as we have now demonstrated, the saturation amplitudes are small and very sensitive to the level of noise in the simulations. These combinations of factors require special care in order to ensure the validity of the results. In order to overcome these problems, we used a formally exact approach for computing the nonlocal Vlasov stability. We then used these linear results as a guide for our high resolution full particle simulations to address the nonlinear evolution of the tearing mode. This combination of work enabled us to address the linear and nonlinear evolution of the tearing mode at the magnetopause.

Our main objective for this work has been to settle the controversial issue regarding the location of reconnection at the magnetopause. In other words, which of the two models of reconnection, anti-parallel merging and component merging, are correct? Since the collisionless tearing mode is thought to be the onset mechanism for reconnection at the magnetopause, we spent the first year working out the details of the linear and nonlinear properties of the collisionless tearing mode for both the anti-parallel and component merging geometries. The results of this research led to new insight on reconnection onset and its subsequent evolution. Details can be found in our three JGR papers, and one GRL. We are also working on a fourth JGR paper. In what follows, we provide some of the highlights of this work.

Linear Theory

Using the exact nonlocal Vlasov linear stability code developed at Los Alamos by the PI at Los Alamos, we found that in general the previous theories provide poor estimates of the linear properties such as the growth rate, and even in some cases the direction of maximum growth. We identified three distinct parameter regimes depending on the degree to which electron orbits are modified by the guide field in the central region of the sheet. In the limit of both weak and strong guide field, the fastest growing tearing mode has a wavevector perpendicular to the direction of the current, in agreement with previous theories. However, for intermediate values of the guide field where the electrons begin to transition to magnetized orbits, the fastest growing modes have a finite wavevector in the direction of the current. These so-called drift tearing modes propagate in the direction of the electron diamagnetic drift with growth rates 10-50% larger than the conventional

tearing instability. We confirmed these new predictions with full particle simulations. Having established the detailed linear properties of the tearing mode, we then compared the growth rate as a function of the guide field. Although the presence of the guide field can reduce the growth rate of the tearing mode, this effect is small and is not enough to rule out component merging at the magnetopause.

Full Particle Simulations

Aside from the linear growth rate, another factor that determines the viability of the tearing mode as an onset mechanism is its saturation amplitude/nonlinear evolution. Unfortunately the nonlinear saturation of the tearing mode, be it for the pure anti-parallel case or the guide field limit, is not understood. Accordingly we developed a theory and compared the predictions with full particle simulations. We found that (a) in case of a single growing mode, tearing mode saturates at minute amplitudes even in the anti-parallel geometry, eliminating it as a viable reconnection mechanism at the magnetopause. (b) In case of a number of growing modes, the nonlinear evolution consists of a three distinct stages that finally leads to explosive growth (Fig.1). Again, this picture remains intact independent of the size of the guide field. (c) We showed that at the magnetopause, there are usually a number of growing modes (Fig.2) and thus tearing mode would be a viable onset mechanism. Given the small differences in both the linear and nonlinear evolution of the tearing mode as a function of the guide field, we concluded that both anti-parallel and component merging should occur at the magnetopause.
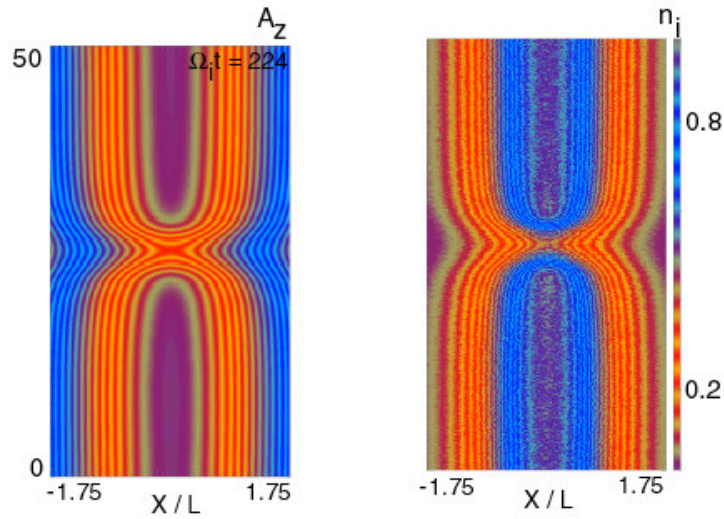
Explosive growth starts when the island amplitude becomes large enough to engulf the low density region of the harris equil.
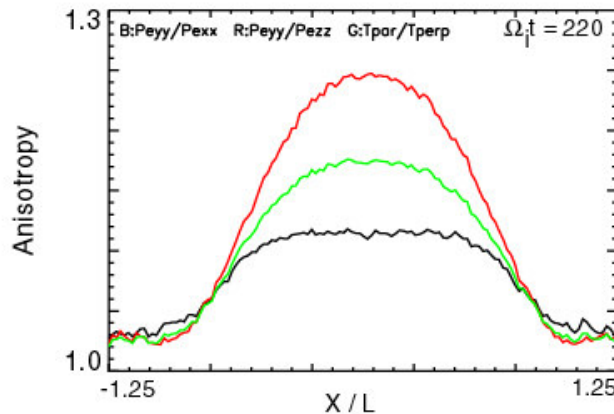
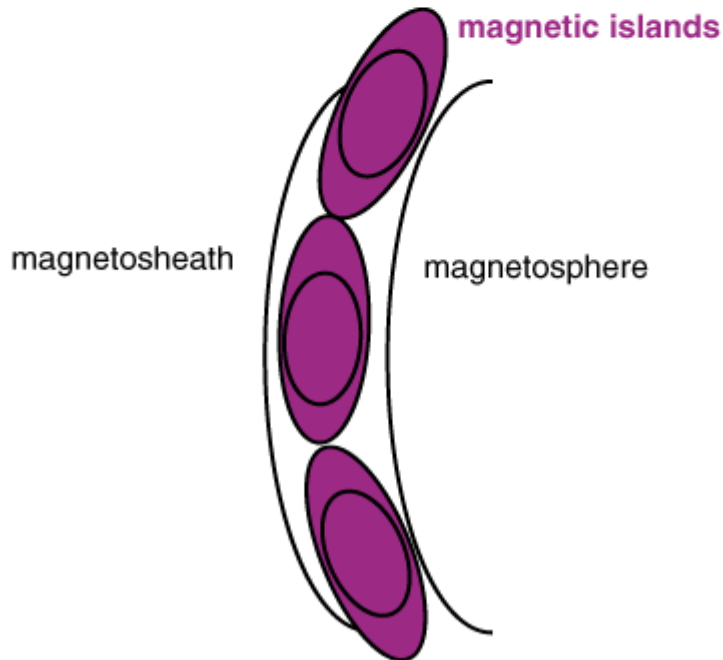## How Many Islands Can Fit into the Magnetopause?

$k L \sim 0.5$

nose to cusp $\sim 6 R_E$

$\rho_i / L \sim 0.1 - 1.0$

$\rho_i \sim 50$ km

→ | No. of Islands > 120 $\rho_i / L \sim 12 - 120$ |

magnetic islands

magnetosheath   magnetosphere

3D and role of Lower Hybrid Instability

In addition to the above work, we also performed a number of 2D and 3D simulations (in collaboration with P. L. Pritchett at UCLA) to assess the role of lower hybrid instability on the current sheet as well as the tearing mode and presented the results at the Fall AGU, 2002. This work is in preliminary stages and will be the focus of our second year effort.

Code development

The main code used for the 2D simulations has been the 2D full particle developed by the Los Alamos PI, W. Daughton. We are in the process of refining and testing a 3D full particle code that the UCSD PI has developed in order to use it for this application. The computations during the first year were performed on Los Alamos computers as well as on the supercomputer accounts that the UCSD PI has. The UCSD PI also has his own cluster consisting of 80 AMD 2600+ cpus and we have performed some of the simulations on that cluster.

Student Progress

We have started two graduate students (J. Driscoll, C. Briscoe) on this project. One of them, Jonathan Driscoll, had a presentation at the Fall AGU. Both students have presentations at the Fall AGU, 2004.

Work Presented at AGU

Karimabadi, H., D. Krauss-Varban, W. Daughton, P. L. Pritchett, and N. Omidi, Stability and Structure of Superthin Sheets: 2D and 3D Full Particle Simulations, Fall AGU, San Francisco, CA, *EOS Trans.*, 2003.

Quest, K. B., H. Karimabadi, and W. Daughton, Component versus Anti-parallel Merging at the Magnetopause: Nonlinear Theory and Particle Simulations, Fall AGU, San Francisco, CA, *EOS Trans.*, 2003.

Driscoll, J., H. Karimabadi, J. Huba, and D. Krauss-Varban, Hybrid and Hall MHD simulations of the out-of-the-plane magnetic field component: Origin and Generation Mechanism, Fall AGU, San Francisco, CA, *EOS Trans.*, 2003.

Karimabadi, H., W. Daughton, and K. B. Quest, Physics of Reconnection Onset and Observable Predictions for the Magnetopause, European Geosciences Union, 1st General Assembly Nice, France, 25 - 30 April 2004.

Papers

Karimabadi, H., W. Daughton, and K. B. Quest, Role of electron temperature anisotropy in the onset of magnetic reconnection, Geophys. Res. Lett., Vol. 31, L18801, doi:10.1029/2004GL020791, 2004 .

Daughton, W., and H. Karimabadi, Linear theory of drift tearing modes at the magnetopause, to appear in *J. Geophys. Res*., 2004.

Karimabadi, H., W. Daughton, and K. B. Quest, Physics of saturation of collisionless tearing mode as a function of guide field, to appear in *J. Geophys. Res*., 2004.

Karimabadi, H., W. Daughton, and K. B. Quest, Anti-parallel versus component merging at the magnetopause: current bifurcation and intermittent reconnection, to appear in *J. Geophys. Res.*, 2004.

Funding

We have submitted one proposal to NASA on this topic and awaiting decision.

II. Revised Work Plan For FY05

Having addressed the onset mechanism in detail in 2D current sheet, we plan to continue our work in 3D. This is inline with our original plans. However, as a result of our research in the first year, we are able to have a more focused approach. We have learned the degree that tearing generates temperature anisotropies and how it affects its nonlinear saturation. We have also developed a better understanding of the LHDI and the ion/ion kink mode. We are now in a position to use this gained knowledge, which was based on 2D studies, to examine the interaction of these instabilities in 3D:

- As we have demonstrated, tearing mode is very sensitive to the sign and degree of electron temperature anisotropy. Tearing mode tends to increase $T_\parallel / T_\perp$ which is stabilizing whereas lower hybrid drift instability (LHDI) tends to increase $T_\perp / T_\parallel$ which is destabilizing for tearing mode. Since LHDI has in general a larger growth rate than the tearing mode, its evolution can significantly modify the current layer before tearing mode has a chance to grow. As a result, it is important to account for the simultaneous presence of LHDI and the tearing mode.

- Guide field tearing has inherently a 3D structure and has resonance surfaces on different planes. This can even lead to percolation. Our finding that the maximum growth can be at oblique angles further complicates this picture and a full 3D treatment is required.

- Other instabilities such as the ion/ion kink mode, either formed due to the presence of a background population or generated due to LHDI, can also affect the growth of the tearing mode.

III. Updated declaration of other ongoing research projects related to the IGPP funded project

We have a number of ongoing research projects related to our IGPP:

1) The PI at UCSD has initiated a collaboration with Gianni Lapenta at Los Alamos and they have a presentation at APS and the Fall AGU meeting on the subject of 3D reconnection.

2) Using Hall MHD and hybrid simulations to understand the role of ion kinetic effects versus the Hall effects. Contrary to current understandings of the reconnection process, we are finding that ion kinetic effects often dominate the Hall term and can even give rise to the quadrupole structure even in the absence of the Hall term.

3) We plan to develop a new equilibrium that incorporates the temperature anisotropy as well as a finite guide field and then use this equilibrium to investigate the detailed linear and nonlinear evolution of various modes in a current sheet. We point out that ions often have a finite temperature anisotropy in the magnetosheath. There is not as much known about the size of temperature anisotropy in electrons. The conventional wisdom has been that any electron anisotropy would quickly get quenched. However, our results demonstrate that even small levels of electron anisotropy can have significant effects on nonlinear properties of various modes. Further, both tearing and LHDI generate electron anisotropies.

IV. Detailed budget request, noting any changes from the original proposal

The main changes in our budget are as follows:

(1) We have two students in the budget, rather than one student in the first year.

(2) We have requested funds for one travel for one of our students.

(3) We have requested $1500 for the purchase of a workstation to be used by our two students.